

I hereby certify that this correspondence is being deposited with the United States Postal Service as Express Mail No. EL961115752US addressed to:

Mail Stop: Patent Application
Commissioner for Patents
PO Box 1450
Alexandria, VA 22313-1450

on December 3, 2003 by Inja Yi.

Dated: 12/3/03

By: Inja Yi

172A 3509 SUZUKI

Applicant(s): TOMIO SATOH

For: TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR

TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR

BACKGROUND OF THE INVENTION

Field of the Invention

5 The present invention relates to a temperature compensated crystal oscillator. Particularly, the present invention relates to a temperature compensation method for a crystal oscillator that is used as a reference frequency in a mobile communication and a satellite communication etc.

10

Description of the Related Art

In recent years, the utilization range of the land mobile communication as represented by portable telephones is expanding steadily. Along this development, the portable telephones are 15 also spreading rapidly, and are involving severe technical development competitions. Crystal oscillators that are used in the portable telephones are also required to have higher performance at low cost in small sizes. The oscillation frequency of the crystal vibrator changes in a cubic curve versus 20 a change in the environmental temperature, as shown in Fig. 23. In order to obtain high stability, an oscillation circuit is provided with a temperature compensation circuit to offset the temperature characteristics of the vibrator. The temperature compensation method is either a direct temperature compensation 25 method or an indirect temperature compensation method. It is general that any one of these method changes the load capacitance of the oscillation circuit thereby to compensate for temperature.

The oscillators used in a PLL circuit (phase-locked loop circuit) are required to have a function of changing the frequency by applying a voltage (V_{cont}) from the outside. An oscillator used in a PLL circuit for a satellite communication is required high 5 stability, therefore, not only V_{cont} function but also a temperature compensated function (circuit) is provided in the oscillator. In other words, two or more variable functions are provided within the oscillation circuits to change the load capacitance and change the frequency. These functions 10 necessarily interfere with the variable ranges. For example, assume that 100ppm of the frequency control range is necessary for the temperature compensation circuit. In this case, when 20ppm of the frequency control range is externally changed by V_{cont} , a ratio of the load capacitance of the temperature 15 compensation circuit to a total load capacitance changes. Therefore, a frequency change due to the change of the load capacitance changes, which results in 99ppm of the frequency control range by a temperature compensation circuit, and this aggravates the temperature characteristics by 1ppm.

20 Fig. 24 is a block diagram of a conventional temperature compensation type crystal oscillator having an external variable capacitance function (V_{cont}). A temperature compensation voltage generator 116 generates a compensation functional voltage, and applies the voltage to a variable capacitance diode 25 114. A load capacitance of the oscillation circuit changes based on a change in the capacitance of the diode. Accordingly, the temperature characteristics of the oscillation frequency of a

crystal oscillator 111 are controlled to be flat. Consequently, the frequency temperature characteristics of the oscillator become excellent. In this case, a voltage is input from an external variable controller (Vcont) 117, and is applied to a variable capacitance diode 115 thereby to change the frequency. This not only changes the oscillation frequency but also affects the temperature compensation quantity.

The temperature compensation quantity and the external variable quantity have a strong relationship with a capacitance ratio of the oscillator ($\gamma = C_o/C_1$) as follows.

1. Basic theory

An equation (1) expresses an offset frequency deviation from a series resonance frequency when the crystal oscillator oscillates.

..... D_I : Oscillation frequency deviation

C₁ : Series capacitance of a vibrator

C_0 : Parallel capacitance (Inter-electrode capacitance) of a vibrator

C : Capacitance of a circuit

Fig. 25 illustrates an oscillation frequency equivalent block diagram expressed by the equation (1).

Fig. 26 illustrates isolation of the C_L into three series quantities of C_x , C_y and C_c as given by an expression (2).

For example, C_x represents a temperature compensation quantity, C_y represents a frequency adjustment or an external variable capacitance, and C_c represents an oscillation circuit 5 capacitance. When $C_o = 0$ (Open), the following equation (3) can be obtained.

$$D_L = \frac{C_1}{2C_L} = \frac{C_1}{2} \left(\frac{1}{C_x} + \frac{1}{C_y} + \frac{1}{C_c} \right) = \frac{C_1}{2C_x} + \frac{C_1}{2C_y} + \frac{C_1}{2C_c} \dots \dots \dots (3)$$

10 As shift quantities of the frequency from the series resonance frequency are added to the capacitances of C_x , C_y , and C_c respectively, the frequency deviation is not interfered with suppression or the like due to the respective capacitances change.

15 However, as a piezoelectric element such as the crystal
vibrator requires an electrode to promote oscillation, the
inter-electrode capacitance C_0 cannot be omitted.

The following equation (4) is obtained from the equations (1) and (2).

$$D_L = \frac{C_1}{2(C_0 + C_L)} = \frac{C_1}{2C_0 \left(1 + \frac{C_L}{C_0}\right)} = \frac{1}{2\gamma \left(1 + \frac{1}{\frac{C_0}{C_L}}\right)} = \frac{1}{2\gamma \left(1 + \frac{1}{\frac{1}{x} + \frac{1}{y} + \frac{1}{c}}\right)} = \frac{1}{2\gamma} \times \frac{x + y + \frac{xy}{c}}{x + y + xy + \frac{xy}{c}} \quad \dots \dots \dots (4)$$

5 $D_L = \frac{1}{2\gamma} F(x, y, c), \dots \dots \dots DS_x = \frac{1}{2\gamma} \frac{dF}{dx}$

$$F(x, y, c) = \frac{x + y + \frac{xy}{c}}{x + y + xy + \frac{xy}{c}}, \dots \dots \dots S_x = \frac{dF}{dx} = \frac{-c^2 y^2}{\{xy + c(x + y + xy)\}^2} \quad \dots \dots \dots (5)$$

$$\gamma = \frac{C_0}{C_1}, x = \frac{C_x}{C_0}, y = \frac{C_y}{C_0}, c = \frac{C_c}{C_0} \quad \dots \dots \dots (6)$$

10 $F(x, y, c)$: A normalization function representing a frequency deviation, when $\frac{1}{2\gamma} = 1$, that is, a capacitance swing = 1.

S_x : A partially differentiated value of $F(x, y, c)$ representing sensitivity of x (i.e., a frequency deviation per unit change).

γ : Capacitance ratio, x : Normalization variable capacitance 1,

y : Normalization variable capacitance 2, c : Oscillation circuit capacitance

15

Fig. 27 illustrates a simulation diagram of $F(x, y, c)$ when $c = 25$, $y = 20, 30$, and 80 , and x is variable. Fig. 28 is an enlarged diagram of the simulation diagram shown in Fig. 27. From the enlarged diagram, it is clear that sensitivity is high and a change in the normalization frequency deviation is large, in a region where x is small.

Fig. 29 illustrates the frequency deviation $D_L(x, y, c)$ and S_x when $\gamma = 200$, that is, when the capacitance swing $1/2\gamma = 2500\text{ppm}$. Fig. 30 illustrates a frequency deviation based on 25 the D_L when $x = 10$. Fig. 31 illustrates a deviation from the D_L curve when $y = 30$ and $x = 10$. In other words, Fig. 31 illustrates a difference of the D_L relative to a value of x in a curve when

$y = 30$ and $x = 10$, and a curve when $y = 80$ and $x = 10$, respectively. In other words, this diagram illustrates a deviation from a reference curve relative to the value of x , that is, interference. As is clear from the diagram, the deviation of each curve becomes 5 larger when the value of x is smaller.

In Fig. 32, the ordinate represents a deviation from the reference curves shown in Fig. 31, and the abscissa represents a frequency deviation when $y = 30$, based on $X = 10$ shown in Fig. 30, that is, a value of the DL. Referring to Fig. 32, when the 10 frequency decreases by 40ppm in x (variable capacitance 1) and when the frequency increases by 30ppm in y (variable capacitance 2), a distortion occurs by about 1ppm. When the frequency decreases by 100ppm, a distortion occurs by about 2.8ppm.

The above distortions indicate that it is necessary to 15 take into consideration the additional functions of the oscillator including two variable controllers, that is, addition of a temperature compensation function to an OCXO (high stability oscillator), addition of a temperature compensation function to a VCXO (voltage control oscillator), and addition of a voltage 20 control function to a TCXO (temperature compensation oscillator).

The oscillator having two or more load capacitance variable functions to change the load capacitance of the external control function of frequency and the temperature compensation function 25 as shown in Fig. 24 has a large problem in that mutual variable capacitance distort the variable quantity or the compensation quantity.

The oscillation frequency of the crystal oscillator can be changed according to three elements of load capacitance, environmental temperature, and oscillator current. Among these elements, the change of frequency according to the change in
5 the load capacitance is used most. The high stability oscillator obtains higher stability by making constant the temperatures of the vibrator and the peripheral circuits. However, there is rare example of changing the frequency by using the vibrator current. Only a part of high stability oscillators is provided
10 with a circuit that suppresses the vibrator current in order to improve aging.

SUMMARY OF THE INVENTION

In the present invention, by utilizing the fact that
15 frequency control according to the vibrator current gives substantially no influence to the change of the load capacitance, the vibrator current is controlled to compensate for the frequency temperature characteristics of the crystal oscillator.

20 In the light of the above problems, it is an object of the present invention to provide a temperature compensated crystal oscillator that can obtain a large variable range and that can obtain high temperature stability that the conventional oscillator having two or more load capacitance variable functions
25 cannot achieve by controlling a vibrator current.

In order to solve the above problems, according to a first aspect of the present invention, there is provided a temperature

compensated crystal oscillator comprising: a oscillation circuit that has a piezoelectric vibrator having a piezoelectric element which is excited in a predetermined frequency, and an oscillation amplifier that excites the piezoelectric element
5 by flowing a current to the piezoelectric element; a vibrator current controller that controls a current of the piezoelectric vibrator; a temperature compensation circuit that compensates for temperature characteristics of the piezoelectric vibrator; and a variable capacitance diode that changes the oscillation
10 frequency by changing the load capacitance of the oscillation circuit using an external voltage, wherein the temperature compensation circuit generates a functional voltage that compensates for the temperature characteristics of the piezoelectric vibrator, and inputs the functional voltage to
15 the vibrator current controller, thereby to control the vibrator current to change the oscillation frequency of the oscillation circuit so as to compensate for the temperature characteristics of the piezoelectric vibrator, and the temperature compensation circuit changes an application voltage of the variable
20 capacitance diode by using the external voltage, thereby to change the oscillation frequency of the oscillation circuit.

The conventional oscillator for PLL circuit (phase-locked loop circuit) is required to have two or more variable functions within the oscillation circuits to change the load capacitance
25 and change the frequency. These functions necessarily interfere with the variable ranges. On the other hand, according to the present invention, a variable capacitance diode is used

in which the temperature compensation circuit generates a functional voltage to control the vibrator current, thereby to change the oscillation frequency of the oscillation circuit so as to compensate for the temperature characteristics of the
5 piezoelectric vibrator, and the temperature compensation circuit changes an application voltage of the variable capacitance diode using the external voltage, thereby to change the oscillation frequency of the oscillation circuit by changing the load capacitance of the oscillation circuit.

10 According to the above aspect of the invention, the vibrator current is controlled to compensate for the temperature characteristics. Therefore, an oscillator having two or more load capacitance variable functions can obtain a large variable range, and at the same time, can obtain high temperature stability
15 without interfering with the mutual variable ranges.

According to a second aspect of the invention, there is provided a temperature compensated crystal oscillator comprising: a oscillation circuit that has a piezoelectric vibrator having a piezoelectric element which is excited in a
20 predetermined frequency, and an oscillation amplifier that excites the piezoelectric element by flowing a current to the piezoelectric element; a vibrator current controller that controls a current of the piezoelectric vibrator; a temperature compensation circuit that compensates for temperature
25 characteristics of the piezoelectric vibrator; and a variable capacitance diode that changes the oscillation frequency by changing the load capacitance of the oscillation circuit using

an external voltage, wherein the temperature compensation circuit generates a functional voltage that compensates for the temperature characteristics of the piezoelectric vibrator, and applies the functional voltage to the variable capacitance diode

5 to change the load capacitance of the oscillation circuit, thereby to change the oscillation frequency of the oscillation circuit so as to compensate for the temperature characteristics of the piezoelectric vibrator, and the temperature compensation circuit changes a voltage to be input to the vibrator current

10 controller using the external voltage, thereby to change the oscillation frequency of the oscillation circuit.

According to the first aspect of the invention, the temperature compensation circuit that compensates for temperature characteristics is connected to the vibrator current controller thereby to compensate for temperature. On the other hand, according to the present aspect, a functional voltage generated by the temperature compensation circuit is applied to the variable capacitance diode, thereby to change the oscillation frequency and compensate for temperature. An external voltage is applied to the vibrator current controller to change the frequency.

According to the present aspect, operation effects similar to those according to the first aspect of the invention can be obtained.

25 According to a third aspect of the invention, a reactance element that changes the oscillation frequency of the oscillation circuit by changing the load capacitance is further inserted

into the load of the oscillation circuit.

When the load capacitance of the oscillation circuit changes, a slope of the frequency deviation at the time of application of a temperature compensation voltage changes. In 5 other words, when the load capacitance is changed, the oscillation frequency can be changed.

According to the present aspect, as the reactance element that changes the oscillation frequency is further inserted, the oscillation frequency can be changed in a simple circuit 10 configuration.

According to a fourth aspect of the invention, a variable reactance element that changes the oscillation frequency of the oscillation circuit by changing the load capacitance is further inserted into the load of the oscillation circuit, and the 15 capacitance of the variable reactance element is changed from the outside of the oscillator thereby to control the oscillation frequency of the oscillation circuit.

When the capacitance of the reactance element can be changed optionally like a variable trimmer, the oscillation 20 frequency can be controlled by externally changing the trimmer.

According to the present aspect, the variable reactance element is used that can optionally change the reactance element like the variable trimmer. Therefore, the oscillation frequency can be easily controlled externally.

25 According to a fifth aspect of the invention, the temperature compensated crystal oscillator further comprises a correction variable capacitance diode that corrects a

compensation distortion generated by changing the load capacitance, wherein the correction variable capacitance diode corrects a compensation distortion generated by changing the load capacitance of the vibrator current controller using a 5 functional voltage that is generated by the temperature compensation circuit.

According to the present aspect, the vibrator current controller comprises the correction variable capacitance diode. Therefore, it is possible to correct for the compensation 10 distortion generated by changing the load capacitance, thereby to further decrease the frequency distortion relative to the application voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

15 Fig. 1 is a block diagram of a temperature compensation system according to the present invention;

Fig. 2 illustrates a circuit diagram to exemplify the temperature compensation system according to the present invention;

20 Fig. 3 illustrates a circuit diagram of a compensation voltage generation circuit to exemplify the temperature compensation system according to the present invention;

Fig. 4 illustrates a circuit example 1 expressing a relationship between D1 application voltage and frequency 25 deviation and vibrator current according to the present invention;

Fig. 5 illustrates a circuit example 2 expressing a

relationship between D1 application voltage and frequency deviation and vibrator current according to the present invention;

Fig. 6 illustrates a circuit example 3 expressing a relationship between D1 application voltage and frequency deviation and vibrator current according to the present invention;

Fig. 7 illustrates a circuit example 4 expressing a relationship between D1 application voltage and vibrator current according to the present invention;

Fig. 8 illustrates a circuit example 5 expressing a relationship between D1 application voltage and frequency deviation according to the present invention;

Fig. 9 illustrates a relationship between measuring results of a variable capacitance diode D1: MA2S304 and approximation function according to the present invention;

Fig. 10 illustrates a circuit example 6 expressing a relationship between D1 variable capacitance and vibrator current according to the present invention;

Fig. 11 illustrates a circuit example 7 expressing a relationship between D1 variable capacitance and frequency deviation according to the present invention;

Fig. 12 illustrates a circuit example 8 expressing a relationship between C_o variable capacitance and frequency deviation according to the present invention;

Fig. 13 illustrates a circuit example 9 expressing a simulation result 1 of a temperature compensation voltage

generation circuit according to the present invention;

Fig. 14 illustrates a circuit example 10 expressing a simulation result 2 of a temperature compensation voltage generation circuit according to the present invention;

5 Fig. 15 illustrates a circuit example 11 expressing a simulation result of vibrator temperature characteristics, temperature compensation frequency deviation, and compensation according to the present invention;

10 Fig. 16 is a block diagram of another example of a temperature compensation system according to the present invention;

Fig. 17 illustrates an example of a distortion correction circuit of a temperature compensation system;

15 Fig. 18 illustrates a circuit example 12 expressing a relationship between D1 application voltage and frequency deviation of a circuit (having a distortion correction circuit) according to the present invention;

20 Fig. 19 illustrates a circuit example 13 expressing a relationship between D1 variable capacitance and frequency deviation of a circuit (having a distortion correction circuit) according to the present invention;

25 Fig. 20 illustrates a circuit example 14 expressing a simulation result of temperature compensation of a circuit (having a distortion correction circuit) according to the present invention;

Fig. 21 illustrates a circuit example 15 expressing a simulation result of temperature compensation of a circuit

according to the present invention;

Fig. 22 is a block diagram of a temperature compensation system (having a distortion correction circuit) according to the present invention;

5 Fig. 23 illustrates a simulation result of temperature characteristics due to difference in cutting angle of an At-Cut vibrator;

Fig. 24 is a block diagram of a conventional temperature compensation system;

10 Fig. 25 illustrates a resonance frequency equivalent block diagram 1;

Fig. 26 illustrates a resonance frequency equivalent block diagram 2;

15 Fig. 27 illustrates a simulation diagram of $F(x, y, c)$ and S_x ;

Fig. 28 is an enlarged diagram of the simulation diagram of $F(x, y, c)$ and S_x ;

Fig. 29 illustrates a simulation diagram of $D(x, y, c)$ and S_x ;

20 Fig. 30 illustrates a simulation diagram of $D(x, y, c)$ and S_x ;

Fig. 31 illustrates a simulation diagram of $\Delta F(x, y, c)$; and

25 Fig. 32 illustrates a simulation diagram of $\Delta F(x, y, c)$ and F .

DETAILED DESCRIPTIONS

Embodiments according to the present invention will be explained in detail with reference to the drawings. Unless specified otherwise, configuration elements, kinds, combinations, shapes, and their relative positions that are described in the embodiments do not limit the range of the present invention, and they are simple explanatory examples.

In general, stress and distortion of crystal of a crystal vibrator have a nonlinear relationship. Therefore, it is confirmed that the resonance frequency changes as follows according to the vibrator current.

$$\dots \frac{\Delta f}{f} = Ki^2$$

.....*i*: Vibrator current

15 **K**: Proper constant determined by cut, vibration mode,
electrode size, etc.

As a method for controlling the vibrator current at the oscillation time, an AGC circuit is added to a part of high stability crystal oscillators (OCXO) to improve the aging.

In the present example, a circuit described in Japanese Patent Application No. 2002-265000 by the same applicant is used. A temperature compensation simulation is carried out utilizing a fact that the vibrator current can be controlled.

Fig. 1 is a block diagram of a temperature compensation method according to the present invention. This temperature

compensation method employs a configuration comprising a oscillation circuit 12 including a crystal vibrator 11 having a piezoelectric element excited in a given frequency and an oscillation amplifier not shown that excites the piezoelectric 5 element by flowing a current to the piezoelectric element, a vibrator current control circuit 13 that controls the current of the crystal vibrator 11, a temperature compensation voltage generation circuit 15 that compensates for temperature characteristics of the crystal vibrator 11, and an external 10 variable capacitance diode 17 that changes the oscillation frequency of the oscillation circuit 12 using an external variable voltage controller 16. The vibrator current control circuit 13 comprises a variable capacitance diode 14 that controls the vibrator current, and capacitors 1 to 3.

15 The outline operation of the configuration shown in this block diagram is as follows. The temperature compensation voltage generation circuit 15 generates a functional voltage that compensates for the temperature characteristics of the crystal vibrator 11, and applies this functional voltage to the 20 vibrator current control circuit 13. The vibrator current control circuit 13 controls the vibrator current of the crystal vibrator 11, thereby to change the oscillation frequency of the oscillation circuit 12 so as to compensate for the temperature characteristics of the crystal vibrator 11.

25 Fig. 2 illustrates a circuit diagram to exemplify the temperature compensation system. Like constituent elements are designated with like reference numerals, and duplicated

explanations will be omitted. Constants are set as follows.

R₁ = 390Ω, R₂ = 1kΩ, R₃/R₄ = 10kΩ, R₅ = 20kΩ, R₆/R₇ = 100kΩ,
C_o = Variable, C₁/C₂ = 27pF, C₃ = 100pF, C₄ = 10pF, C₅/C₆ = 10000pF,
5 C₇ = 0pF, C₈/C₉ = 0.1μF, TR₁/TR₂ = 2SC3732, D₁ = MA2S304, Xtal
= 26MHz·At-Cut1st, VCC = 5Vdc, VD = DC power supply, V.V = High
frequency voltmeter, and Freq.C. = Frequency counter.

The oscillation circuit is a Colpitts oscillator circuit
10 in cascade connection. The Colpitts oscillator circuit
supplies an oscillation output to the vibrator current control
circuit 13 that is inserted and connected between the collector
of the transistor TR₁ and the emitter of the transistor TR₂.
The temperature compensation voltage generation circuit 15 is
15 connected to the vibrator current control circuit 13 via the
resistors R₆ and R₇, thereby to supply a functional voltage.

Fig. 3 illustrates a circuit diagram of the temperature
compensation voltage generation circuit 15 and a circuit diagram
of the vibrator current control circuit 13 according to the
20 present invention. Like constituent elements are designated
with like reference numerals, and duplicated explanations will
be omitted. Constants at the time of the simulation of the
temperature compensation voltage generation circuit 15 are given
as follows.

25

R₁ · 3 · 4 = 10kΩ, R₂ = 6.5kΩ, R₅ = Variable adjustment, D₁ = 1S953,
IC₁ = TC75S51FU

R10=10k Ω , R11=30k Ω , IC2= TC75S51FU
 R12=10k Ω , R13=140k Ω , IC3= TC75S51FU
 R14=10k Ω , R15=140k Ω , IC4= TC75S51FU
 R6=9.6k Ω , R7=11.1k Ω , R8=11.3k Ω , R9=8k Ω ,
 5 R16·17·18·21·22=100k Ω , R19·20=200k Ω , D2=MA2S304, C3·4·5=0.1 μ F
 Xtal=13MHz, γ =240, C_o =1.35pF, C_p =40pF, C_s =35pF
 Vcc=3.0V,

Fig. 4 illustrates a relationship between D1 application
 10 voltage and frequency deviation and vibrator current, where the
 capacitance C_o = 20pF, and the voltage applied to the variable
 capacitance diode D1 is changed by changing the voltage of the
 variable diode VD. The ordinate expresses a deviation based
 on the frequency when $VD = 1V$, and the abscissa expresses a voltage
 15 applied to the variable diode VD and the variable capacitance
 diode D1.

Similarly, Fig. 5 shows a result when the capacitance C_o
 = 12pF, and Fig. 6 shows a result when the capacitance C_o = 43pF.
 From these diagrams, it is clear that the oscillation frequency
 20 and the vibrator current show similar changes relative to the
 applied voltage to D1.

The vibrator current is obtained from the following
 expression (7).

25 I_x (Xtal Current) = ωCV(7)

V: Voltage at both ends of C_3 : VV unit rms

C : Capacitance of C_3 : 100pF

$\omega = 2\pi f$ $f = 26MHz$

Fig. 7 illustrates a change in the vibrator current having each C_o as a parameter relative to a change in the voltage of the VD. As shown in Fig. 7, it is clear that the change in the vibrator current does not substantially depend on the value of 5 C_o .

Fig. 8 illustrates a frequency deviation having each C_o as a parameter relative to a change in the voltage of the VD. From Fig. 8, it is clear that the change quantity is slightly different depending on the value of C_o .

10 Fig. 9 illustrates a relationship between a voltage applied to the variable capacitance diode D1: MA2S304 and capacitance change characteristics. Fig. 9 illustrates measured data and approximation function. From Fig. 9, it is clear that the measured data coincides well with the approximation function.

15 Fig. 10 illustrates a vibrator current versus capacitance change of the variable capacitance diode D1. From Fig. 10, it is clear that the vibrator current is not substantially affected by a change of the capacitance C_o .

20 Fig. 11 illustrates a frequency deviation versus capacitance change of the variable capacitance diode D1, based on a reference where $VD = 1\text{Vdc}$, and $CV = 26\text{pF}$. Fig. 11 illustrates approximation function using each C_o as a parameter.

Fig. 12 illustrates a change in the oscillation frequency when the capacitance C_o is variable. $C_o = 20\text{pF}$ is a reference. 25 The capacitance of the D1 is set as follows. $VD = 1\text{Vdc}$, that is, $CV = 26\text{pF}$. As a result, when C_o is changed from 12pF to 43pF , a change of about 280ppm is obtained as a frequency

deviation.

Fig. 13 illustrates a result of a simulation carried out using the circuit constants. In Fig. 13, each symbol represents a voltage change of a portion of each respective symbol in Fig.

5 3.

[a] represents a monotonous decrease relative to the temperature change in the output from the operation amplifier IC1.

[b] represents a monotonous increase from near 0 °C to 10 near 50 °C to compensate for a change in the vicinity of an inflection point of the vibrator in the output from an operation amplifier IC2.

[c] represents a monotonous increase from near -30 °C to 15 near -10 °C to compensate for a low temperature side of the vibrator in the output from an operation amplifier IC3.

[d] represents a monotonous increase from near 65 °C to near 90 °C to compensate for a high temperature side of the vibrator in the output from an operation amplifier IC4.

Fig. 14 illustrates a voltage change at each portion of 20 the temperature compensation voltage generation circuit 15 shown in Fig. 3. [e] represents a voltage change based on a combination of [b] and Vcc. [f] represents a voltage change based on a combination of [c] and [d]. [VD] represents a change in the voltage between the cathode and the anode of the variable 25 capacitance diode.

Fig. 15 illustrates a result of carrying out a temperature compensation simulation according to an oscillation frequency

deviation due to a change in the variable capacitance diode D1 that controls the vibrator current based on Fig. 11.

In other words, the variable capacitance diode D1 that controls the vibrator current receives a compensation voltage 5 from the temperature compensation voltage generation circuit 15, thereby to change the capacitance of the vibrator current control circuit 13. From Fig. 11, parallel capacitances C7, C8, and C9 are set to properly compensate for the temperature characteristics of the vibrator based on a relational expression 10 of the capacitance change versus frequency deviation using C_o as a parameter. The temperature compensation simulation is carried out based on the following setting. 1. $C_o = 20\text{pF}$, $C7 = 5\text{pF}$, and $C8/C9 = 66\text{pF}$. As a result of the simulation, the temperature characteristics $\pm 2\text{ppm}$ or less are obtained within 15 a temperature range from $-30^{\circ}\text{C} \sim +85^{\circ}\text{C}$.

2. Based on the above setting, that is, " $C7 = 5\text{pF}$, and $C8/C9 = 66\text{pF}$ ", C_o is changed to $C_o = 12\text{pF}$ and $C_o = 43\text{pF}$. As a result, when $C_o = 12\text{pF}$, the frequency rises by about 0.8ppm in the vicinity of 0°C , and the frequency falls by about 0.8ppm 20 in the vicinity of 55°C . When $C_o = 43\text{pF}$, the frequency falls by about 1ppm in the vicinity of 0°C , and the frequency rises by about 1ppm in the vicinity of 55°C .

From the result of the C_o versus frequency deviation shown in Fig. 12, it is clear that when the load capacitance of C_o 25 is changed from 20pF to 12pF , the frequency rises by 150ppm, and when the load capacitance of C_o is changed from 20pF to 43pF , the frequency falls by 130ppm.

In other words, these frequency changes cannot be obtained based on the temperature compensation and external variable control according to the conventional load capacitance change method only.

5 Fig. 16 is a block diagram illustrating another example of the temperature compensation system according to the present invention. Like constituent elements are designated with like reference numerals, and a duplicated explanation will be omitted. Fig. 16 is different from Fig. 1 in that the positions of the
10 temperature compensation voltage generation circuit 15 and the external variable voltage controller 16 are different. In other words, the external variable voltage controller 16 controls the vibrator current control circuit 13, and the temperature compensation voltage generation circuit 15 changes the
15 capacitance of the variable capacitance diode 17 to compensate for temperature.

As explained above, according to the present invention, the vibrator current is controlled to change the frequency to compensate for the temperature characteristics of the crystal
20 vibrator. When the frequency needs to be changed according to an external control, the load capacitance is changed according to the conventional method.

With the above arrangement, mutual interference is not present, and particularly, frequency can be changed significant
25 based on the external variable voltage control. As there is less interference to the temperature compensation quantity due to the external variable voltage control, excellent temperature

characteristics can also be obtained. This is expected to make a large contribution to the future functional expansion of the crystal oscillator and the piezoelectric oscillator.

Fig. 17 illustrates a circuit that corrects a difference 5 in frequency deviation (compensation distortion due to a load capacitance change) based on a voltage application to the variable capacitance diode D1 that controls the vibrator current according to the value of the load capacitance shown in Fig. 8. The control quantity of the vibrator current control system 10 according to the present invention is determined based on the ratio of collector-emitter capacitance to the emitter-GND capacitance. The control quantity becomes larger when the emitter-GND capacitance is smaller than the collector-emitter capacitance.

15 Based on the above fact, the external voltage Vc is changed to control the variable reactance element (i.e., variable capacitance diode D2) thereby to change the load capacitance to change the frequency. At the same time, the variable reactance element (i.e., variable capacitance diode D3) is inserted into 20 between the emitter and the GND, and the external voltage Vc is applied to change the capacitance of the diode. With the above arrangement, the compensation distortion due to the change in the load capacitance following the control of the variable capacitance diode D2 can be corrected. In this case, the load 25 capacitance is made small to change the frequency to be high, and the capacitance between the emitter and the GND is made small to increase the compensation quantity thereby to correct the

distortion. This further makes smaller the load capacitance. The fact that the distortion correction control and the frequency change control can be carried out at the same time has a large effect.

5 Fig. 18 illustrates a result of carrying out the measurement by taking the following measure to the capacitor C_o that is connected to in series with the vibrator.

$C_o = 20\text{pF}$... emitter-GND capacitance: $C_2 = 27\text{pF}$ is the basis. Distortion correction control is carried out based on
10 $C_o = 12\text{pF}$... emitter-GND capacitance: $C_2 = 18\text{pF}$, $C_o = 43\text{pF}$...
emitter-GND capacitance: $C_2 = 30\text{pF}$. Fig. 18 illustrates a frequency deviation due to the voltage application to the variable capacitance diode D1 that controls the vibrator current.

Based on the result of Fig. 8 before the correction, the
15 difference (distortion value) = about 8ppm relative to $VD = 2\text{Vdc}$ before the correction. The difference (distortion value) = about 2ppm relative to $VD = 2\text{Vdc}$ after the correction. This becomes the improvement from the distortion (dependency of the capacitance C_o in the D1 application voltage versus frequency
20 deviation characteristics).

Fig. 19 illustrates a relationship between the capacitance change of the variable capacitance diode D1 that controls the vibrator current and the frequency deviation when the distortion is corrected.

25 Fig. 20 illustrates a simulation result of temperature characteristics when the correction distortion is carried out.

Fig. 21 illustrates a result of the temperature

characteristics simulation shown in Fig. 15, that is, before the distortion correction.

From the above results, it is clear that when the distortion quantity is about 1.6ppm before the correction, the distortion 5 is corrected to about 0.4ppm by carrying out a correction, which is about one quarter of the distortion.

As explained above, according to the first aspect of the present invention, the vibrator current is controlled to 10 compensate for the temperature characteristics. Therefore, an oscillator having two or more load capacitance variable functions can obtain a large variable range, and at the same time, can obtain high temperature stability without interfering with the mutual variable ranges.

15 According to the second aspect of the invention, the effect similar to that obtained from the first aspect of the invention can be obtained.

According to the third aspect of the invention, as a reactance element that changes the oscillation frequency is 20 further inserted, the oscillation frequency can be changed in a simple circuit configuration.

According to the fourth aspect of the invention, the variable reactance element is used that can optionally change the reactance element like a variable trimmer. Therefore, the 25 oscillation frequency can be easily controlled externally.

According to the fifth aspect of the invention, the vibrator current controller comprises the correction variable

capacitance diode. Therefore, it is possible to correct the compensation distortion generated by changing the load capacitance, thereby to further decrease the frequency distortion relative to the application voltage.